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Crowded visual search in children with normal vision and children with visual impairment

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ABSTRACT

This study investigates the influence of oculomotor control, crowding, and attentional factors on visual search in children with normal vision ([NV], $n = 11$), children with visual impairment without nystagmus ([VI−nys], $n = 11$), and children with VI with accompanying nystagmus ([VI+nys], $n = 26$). Exclusion criteria for children with VI were: multiple impairments and visual acuity poorer than 20/400 or better than 20/50. Three search conditions were presented: a row with homogeneous distractors, a matrix with homogeneous distractors, and a matrix with heterogeneous distractors. Element spacing was manipulated in 5 steps from 2 to 32 minutes of arc. Symbols were sized 2 times the threshold acuity to guarantee visibility for the VI groups. During simple row and matrix search with homogeneous distractors children in the VI+nys group were less accurate than children with NV at smaller spacings. Group differences were even more pronounced during matrix search with heterogeneous distractors. Search times were longer in children with VI compared to children with NV. The more extended impairments during serial search reveal greater dependence on oculomotor control during serial compared to parallel search.

1. Introduction

Children with visual impairment (VI) show weaker visual search performance than children with normal vision (NV) (Tadin et al., 2012). Visual acuity is only moderately related to the degree of visual search performance in observers with VI, indicating that other factors also play a role (MacKeben & Fletcher, 2011; Tadin et al., 2012). In the present study, a visual impairment was defined as having visual acuity equal to or better than 20/400 and equal to or poorer than 20/50. There are at least three factors that can influence visual search performance of children with VI: (i) oculomotor control (MacKeben & Fletcher, 2011), (ii) crowding (the inability to identify target objects when they are surrounded by visual clutter: Whitney & Levi, 2011), and (iii) attention, i.e. the mechanism enabling us to select relevant information out of irrelevant noise (Carrasco, 2011; Carrasco, Ling, & Read, 2004). It should be kept in mind that these three factors are interdependent. For example, brain areas involved in visuo-motor modules are also involved in spatial attention networks (Braddick & Atkinson, 2011), and visual search task characteristics (e.g., element spacing) influence oculomotor behaviour (van Zoest, Donk, & Theeuwes, 2004; Vlaskamp, Over, & Hooge, 2005). Therefore, the aim of this study is not to disentangle the contributions of these factors, but to investigate under which circumstances visual search impairment is greatest in children with VI. The motivation for the present study is to expand our understanding of the (combined) contribution of these factors to impaired visual search performance in children with VI. Besides scientific reasons, this is important in order to develop effective rehabilitation programs for these children.

Poor oculomotor control can set a limitation on visual search performance (Liu, Kuyk, & Fuhr, 2007; MacKeben & Fletcher, 2011). The decision of where and when to move the eyes is strongly influenced by the characteristics of the specific search task and the density of the visual array, as well as the viewer strategies (van Zoest & Donk, 2004; van Zoest, Donk, & Theeuwes, 2004). The presence of involuntary ocular oscillations (i.e., nystagmus) during visual search might degrade performance, because of the need for refixations after an involuntary eye movement. A large part of the population of children with VI experiences nystagmus due to the presence of an ocular disorder, while there are also children with VI due to 'idiopathic' or 'motor' nystagmus (Fu et al., 2011). The degree of fixational instability in nystagmus is correlated with the degradation of visual acuity (Simmers, Gray, & Winn, 1999). Up to now, there are no studies in children with VI that have analyzed

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oculomotor behaviour during visual search, but it is to be expected that search times are longer for children with VI with accompanying nystagmus (VI+nys) due to the need for refixations.

A second factor setting a limit on visual search performance is crowding. Crowding occurs when target perception is deteriorated by the presence of nearby contours or patterns and can be minimized when contours are placed at a distance beyond the threshold at which distractors interfere with target recognition (‘critical distance’) (see Levi, 2008, for a review). Visual information from the periphery is used to guide eye movements and a breakdown of this information by crowding can degrade saccadic search (de Vries et al., 2011; Vlaskamp & Hooge, 2006). During visual search in adults with NV, decreasing the element spacing to distances smaller than 1.5° causes longer search times, longer fixation durations, more fixations, and smaller saccades (Vlaskamp, Over, & Hooge, 2005). In addition to element spacing, stimulus configuration can also influence the strength of the phenomenon. In central vision, surrounding distractors placed above, below and on both lateral sides of the target are more potent elicitors of crowding than laterally placed distractors (Atkinson et al., 1985; Toet & Levi, 1992; Vlaskamp & Hooge, 2006). Increasing object density degrades visual search performance in adults with VI (Dougherty et al., 2009; Liu, Kuyk, & Fuhr, 2007). There is evidence that crowding effects are stronger in children with VI than in children with NV at 8° eccentricity (Tadin et al., 2012) and in central vision (Huurneman et al., 2012a). Furthermore, crowding effects in central vision are even stronger for children with VI+nys than children with VI−nys (Huurneman et al., 2012a). These findings are in line with studies reporting stronger lateral interactions in adults with nystagmus (Chung & Bedell, 1995; Huurneman et al., 2012b; Pascal & Abadi, 1995). Thus, it might be expected that children with VI, especially children with VI+nys, experience small spacing as a bottleneck during search performance.

Spatial attention is the third limiting factor in visual search tasks (Carrasco, 2011). Search tasks with homogeneous distractors (i.e. parallel search) are considered preattentive, and tasks with heterogeneous distractors (i.e. serial search) require focal attention (Casco, Gidiuli, & Grieco, 2000; Treisman & Gelade, 1980). Children from the age of 6 years onwards show improved performance on serial search tasks (Ruskin & Kaye, 1990), which could be related to improvements in attentional top-down control (Hommel, Li, & Li, 2004). There is evidence that children with ophthalmic disorder, i.e. children with corrected-to-normal visual acuity, but a history of strabismus, nystagmus or cataract, have attentional impairments as demonstrated by omissions during cancellation tasks and slower execution times than children with NV (Cavezian et al., 2013). As reported above, children with VI show impaired visual search performance (serial search in a wide-field naturalistic display) and stronger peripheral crowding effects, which might both be caused by limited attentional resolution (Carrasco, 2011; Tadin et al., 2012). Because of the reported attentional impairments of children with VI, these children might show disproportionately poor performances on serial tasks compared to children with NV.

The contribution of the above mentioned factors on visual search performance will be investigated in three visual search tasks. The role of oculomotor control is investigated by comparing performance of children with VI+nys with children with VI−nys or NV. The role of crowding is investigated by manipulating element spacing and stimulus configuration (row versus matrix search). Finally, homogeneous and heterogeneous distractors were used so as to manipulate attentional load during task performance. Three hypotheses were evaluated: (i) children with VI+nys show poorer performance than children with NV on visual search tasks with small element spacing, (ii) there are no group differences in the row configuration, but children with VI are expected to show weaker performance than children with NV in the matrix configuration with homogeneous distractors, and (iii) children with VI show a disproportionately poor search performance on serial tasks compared to children with NV.

2. Method

2.1. Participants

Eleven children with NV, 11 children with VI without nystagmus (VI−nys), and 26 children with VI with accompanying nystagmus (VI+nys) participated. Inclusion criteria for all groups were: (a) age between 6 and 8 years, (b) normal developmental level, (c) birth at term (⩾36 weeks of gestation), and (d) birth weight ⩾3000 g. Inclusion criteria for the children with VI was visual acuity between 20/400 and 20/50. Exclusion criteria were the presence of multiple impairments and/or central scotomas. Table 1 presents the characteristics of the children (age, distance visual acuity, and near visual acuity). Clinical characteristics of patients can be found in Table 2. Children with NV were included from regular primary schools in the Netherlands. Children with VI were included from client databases of all Dutch vision rehabilitation centres.

Written consent was obtained from the parents of the participants. A local ethics committee approved the study before the assessments were conducted (CMO Arnhem Nijmegen). The study was conducted in accordance with the Declaration of Helsinki.

2.2. Ophthalmological examination

All children were examined ophthalmologically before the experiment started. Visual acuity was measured binocularly at 6 m with the tumbling E-chart at 6 m (Taylor, 1978) under controlled lighting conditions. Near visual acuity was determined with the LH-version of the *C*-test at 40 cm, which contains a crowded version with interoptotype spacing of 2.6′ (′ refers to minutes of arc) and an uncrowded version with interoptotype spacing of at least 30′ (Haase & Hohmann, 1982; Huurneman et al., 2012a; Hyvarinen, Nasanen, & Laurinen, 1980).

A gross estimation of the visual field was obtained by confrontational techniques. Testing central visual fields was not yet possible in these young children. However in near vision tasks there were no signs of central scotomas. Objective refraction was obtained after cycloplegia and if necessary the spectacle correction was prescribed or changed before the experiment started. Children with glasses had to wear them during the entire study.

2.3. Procedure

Children sat at a distance of 60 cm from the monitor wearing their best available optical correction. Viewing was binocular.

Table 1
Characteristics of children with normal vision (NV), children with visual impairment without nystagmus (VI−nys), and children with VI with accompanying nystagmus (VI+nys). Mean age, distance and near visual acuity (decimal notation), and near visual acuity as determined with the staircase method are given. Numbers in parentheses are standard deviations.

	NV	VI−nys	VI+nys
Age in months	92 (12)	90 (11)	90 (10)
N	11	11	26
DVA[a]	1.17 (0.08)	0.28 (0.12)	0.25 (0.10)
NVA[b]	1.70 (0.38)	0.41 (0.14)	0.35 (0.16)
NVA staircase	n.a.	0.42 (0.14)	0.35 (0.14)

[a] Distance visual acuity (DVA) measured with E-gratings at 6 m.
[b] Near visual acuity (NVA) measured with LH-single symbols at 40 cm.

Table 2
Causes of visual impairment in the two patient groups.

ID	Clinical diagnosis	Binocular DVA[a]
Children with visual impairment without nystagmus		
115	Cone dystrophy	0.30
121	Oculocutaneous albinism	0.36
127	Oculocutaneous albinism	0.36
133	Cone dystrophy	0.30
135	Congenital glaucoma	0.12
140	Corneal opacities	0.36
147	Congenital Stationary Night Blindness	0.36
156	Congenital glaucoma	0.15
160	Hypermetropia (>4D)	0.36
170	Myopia (>6D)	0.40
175	Coloboma irides	0.36
Children with visual impairment with accompanying nystagmus		
101	Albinism	0.12
103	Congenital nystagmus	0.24
107	Hypermetropia (>4D)	0.36
109	Congenital cataract (aphakia)	0.18
112	Congenital nystagmus	0.36
114	Albinism	0.24
116	Albinism	0.08
117	Albinism	0.12
119	Albinism	0.36
123	Albinism	0.36
126	Congenital nystagmus	0.36
131	Congenital Stationary Night Blindness	0.24
132	Myopia (>6D)	0.18
136	Congenital nystagmus	0.36
139	Papildysplasia	0.36
141	Congenital cataract (aphakia)	0.12
149	Congenital nystagmus	0.24
154	Congenital Stationary Night Blindness	0.30
159	Albinism	0.20
163	Juvenile X-linked retinoschisis	0.24
164	Albinism	0.24
165	Congenital nystagmus	0.12
167	Congenital Stationary Night Blindness	0.12
168	Congenital nystagmus	0.36
169	Aniridia	0.40
174	Albinism	0.20

[a] DVA = distance visual acuity as measured with E-gratings (decimal notation).

Before the children performed the search tasks, a three-up one-down 75% correct threshold stair-case method was used to determine the smallest identifiable LH-symbol (house, square, circle and apple; Hyvarinen, Nasanen, & Laurinen, 1980).

Three visual search conditions were presented with symbols at double the threshold size, so as to guarantee visibility for the children with VI (MacKeben & Fletcher, 2011). For children with VI−nys the average symbol size was 0.57°, and for the children with VI+nys this was 0.67°. Children with NV served as a control group and were presented with the same size symbols as the children with VI+nys (0.67°). Two simple search tasks with homogeneous distractors and one complex search task with heterogeneous distractors were presented (see Fig. 1). The instruction in all search tasks was to identify the unique symbol. The location of the unique symbol was randomly varied to make sure the child had to actively search for it. Tasks were presented in block form in random order.

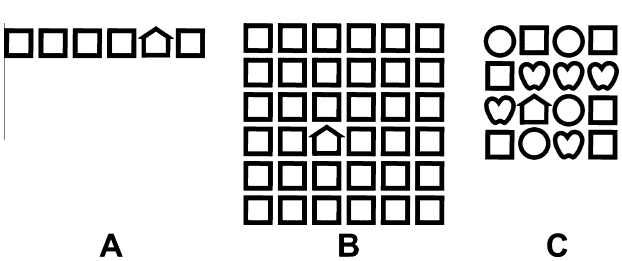


Fig. 1. Examples of the visual search stimuli: (A) row with homogeneous distractors, (B) matrix with homogeneous distractors, and (C) matrix with heterogeneous distractors.

The influence of crowding was measured by manipulating spacing, with edge-to-edge element spacing at 2′, 4′, 8′, 16′ and 32′. Four trials were presented at every spacing for each task, giving 20 trials per task, adding up to a grand total of 60 trials in the experiment. Spacing was fixed for the visual search tasks. This in line with research reporting that charts with fixed spacing are most sensitive to pick up crowding effects (Graf, Becker, & Kaufmann, 2000; Haase & Hohmann, 1982; Huurneman et al., 2012a). Each next trial was presented after the child pressed the response button on the button box.

2.4. Apparatus

Stimuli were generated by a Windows XP computer and presented on a 17 inch TFT monitor with integrated eye-trackers (Tobii T120, Tobii Corporation, Danderyd, Sweden). Stimulus presentation was driven by custom-written Delphi code provided by the scientific programmer of our research institute. We did not fix the head positions of the children. A rule was incorporated into the stimulus-presentation software to assure that the children were seated at a proper viewing distance. When children came closer to the monitor than 60 cm, the stimulus disappeared from the screen, and reappeared if they were seated at 60 cm or more again. This rule was included to prevent children from reducing their viewing distance, as well as to standardize our measurements. Eye movements were registered at 60 Hz sampling rate. Before the visual search tasks were presented, a standard 5-point eye-tracker calibration procedure was performed for both eyes. Fixations were detected offline and were defined as periods in which eye velocity remained below an adaptively determined threshold for at least 50 ms. The velocity threshold was calculated as 3.5 times the standard deviation of the eye velocity below 25°/s and was recalculated for each session.

2.5. Statistical analysis

The presentation of results is divided into two sections: [1] Effects of homogeneous distractors on target detection, and [2] Effects of heterogeneous distractors on target detection. Visual search performance was quantified by two dependent variables: accuracy, defined as the mean percentage of correct responses (i.e. the total count of correct trials divided by the total number of trials), and search time, defined as the mean response latency for correct trials. Eye-movement data were used when eye movements were correctly recorded in at least 60% of the total recording time for each trial. The data of children with less than 10 valid trials per condition were removed. The following dependent variables were measured: number of fixations (mean), fixation duration (mean), and saccade amplitude (mean).

We used nonparametric statistical tests (Kruskal–Wallis for between-group effects and Friedman's tests for within-group effects of spacing), because of unequal variances and skewed distributions. Post hoc tests were conducted by making pairwise comparisons. A correction for pairwise comparisons (Type 1 errors) was made by reporting the adjusted p-value in which the K refers to the number of groups ($p_{adj} = p * K(K-1)/2$; Daniels, 1990).

A partial correlation analysis was conducted to investigate relations between oculomotor and performance measures in the VI+nys group while controlling for visual acuity. This analysis was conducted for the VI+nys group, because of special interest between oculomotor control and search performance. The relations between the following variables was investigated for simple matrix search and complex matrix search with spacing of 2′: accuracy, search time, crowding ratio (i.e. the ratio of single acuity and line acuity (Pardhan, 1997)), number of fixations, fixation duration, and saccade amplitude.

3. Results

3.1. Effect of homogeneous distractors

3.1.1. Performance measures: accuracy and search times

Results are shown in Figs. 2–4. A complete overview of descriptive and test statistics of performance measures is reported in Supplement S1; here, we only report statistically significant results and trends. Groups differed in accuracy: children in the VI+nys group showed lower accuracies than children in the NV group during row (at 2′ and 8′; p's < 0.05; Fig. 2A) and matrix search (at 2′ and 4′; p's < 0.05; Fig. 3A). Spacing only affected accuracy during matrix search in children in the VI+nys group. They were less accurate at smaller spacings than larger spacings (2′, 4′ < 16′, 32′, p's < 0.05; Fig. 3A).

Search times were about 2 times longer during row search and up to 5-fold longer for matrix search for children with VI than children with NV (p's < 0.01; Figs. 2B and 3B). Spacing also affected search times: children in the NV group were quicker at smaller spacings during row search (2′, 4′ < 8′, 32′, p's < 0.1; Fig. 2B) and slower at the smallest spacing during matrix search (2′ > 16′, 32′, p's < 0.1; Fig. 3B). Children in the VI+nys group were slower at 4′ than 8′ during row search. Children in both VI groups were slower at smaller spacings during matrix search (VI−nys: 2′ > 4′–32′, p's < 0.05; VI+nys: 2′, 4′ > 8′–32′, p's < 0.1; Fig. 3B).

In sum, children in the VI+nys group showed lower accuracies at smaller spacings during simple row and matrix search than children in the NV group. In addition, search times were up to 5-fold longer for children in the VI groups compared to children in the NV group.

3.1.2. Eye movements

Statistics of eye movements are reported in the Supplementary Table S2. We collected 29 valid eye-movement recordings for row

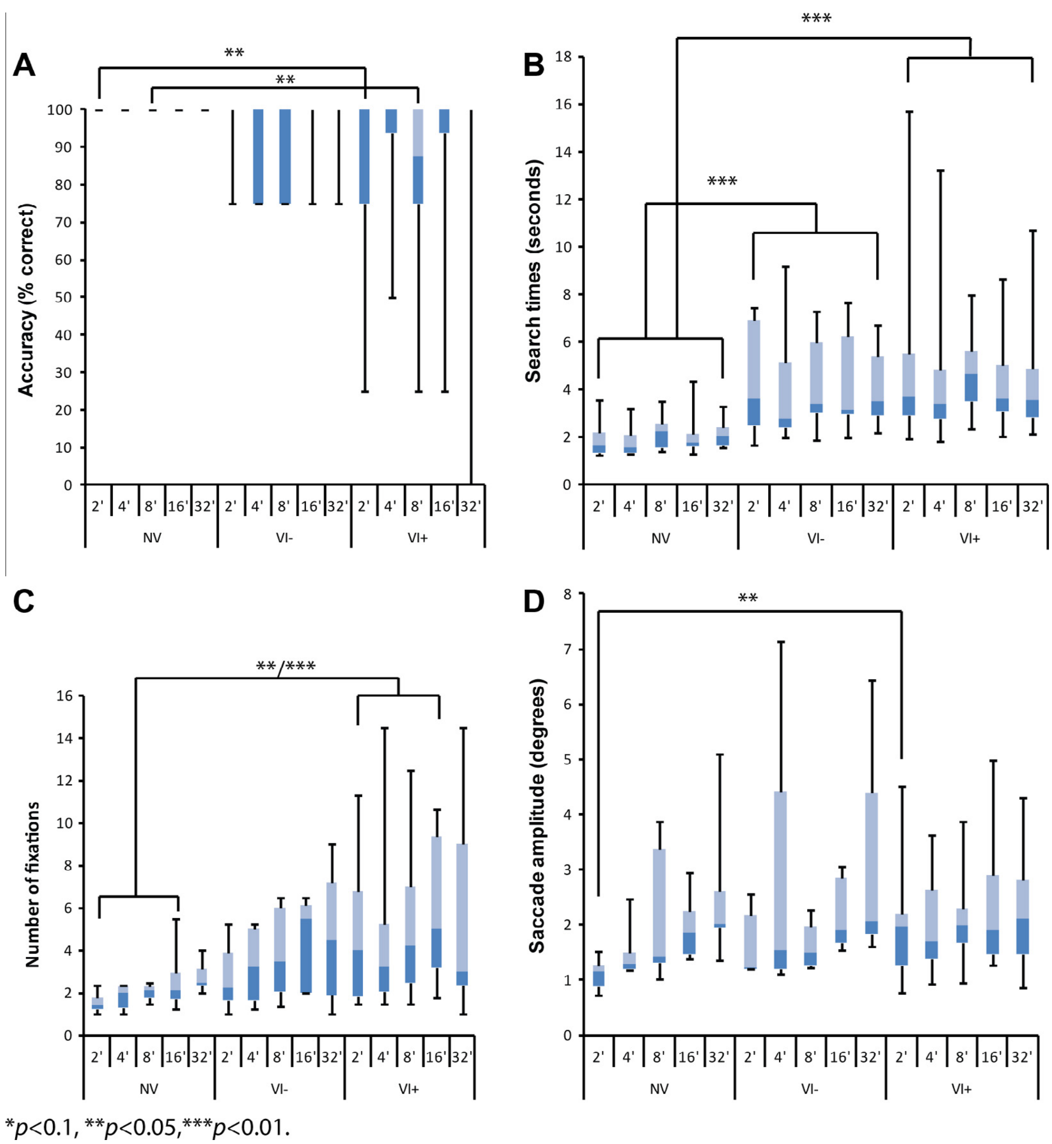
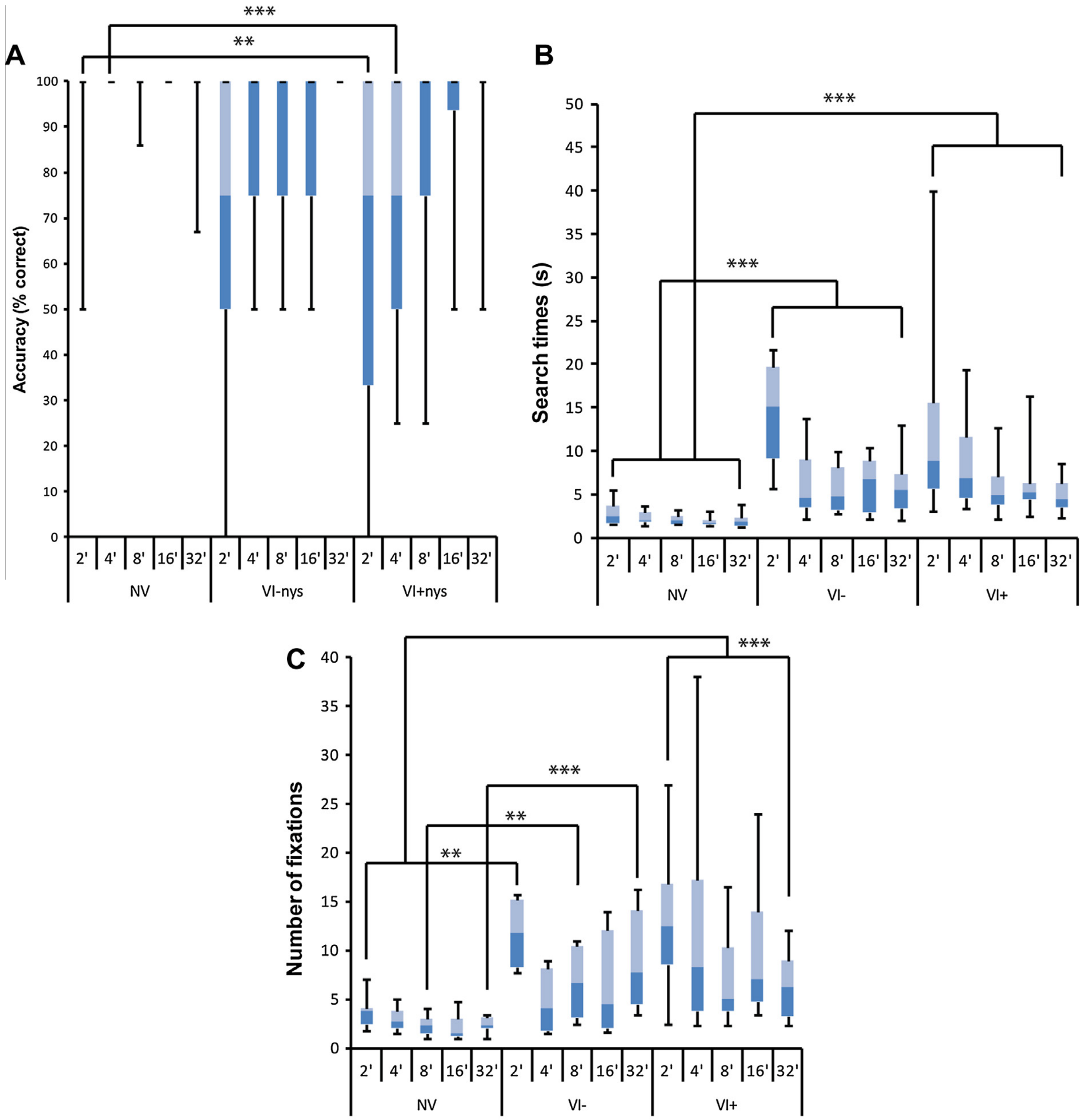


Fig. 2. Box–whisker plots for the distribution of dependent variables in the *row configuration*: (A) accuracies, (B) search times, (C) number of fixations, and (D) saccade amplitudes. The categories on the *X*-axis are the experimental groups: children with normal vision (NV), with visual impairment without nystagmus (VI−), and with visual impairment showing nystagmus (VI+) and the stimulus spacings. *Boxes* and *whiskers*: quartiles and range, respectively.



*p<0.1, **p<0.05,***p<0.01.

Fig. 3. Box–whisker plots for the distribution of dependent variables in the *matrix configuration*: (A) accuracies, (B) search times, (C) number of fixations. The categories on the *X*-axis are representative of groups: children with normal vision (NV), with visual impairment without nystagmus (VI−), and with visual impairment showing nystagmus (VI+). *Boxes* and *whiskers*: quartiles and range, respectively.

search (NV: 8; VI−nys: 5; VI+nys: 16), and 28 valid recordings for matrix search (NV: 9; VI−nys: 4; VI+nys: 15).

Groups differed in number of fixations during simple row search: children in the VI+nys group made more fixations than children in the NV group, except at 32′ (p's < 0.05; Fig. 2C). During simple matrix search there were more pronounced group differences: children in both VI groups made more fixations than children in the NV group (VI+nys all spacings, p's < 0.01; Fig. 3C; VI−nys 2′, 8′, and 32′, p's < 0.05; Fig. 3C). Spacing influenced number of fixations during row search only in children in the NV group: they made fewer fixations at 2′ than 32′ spacing ($p < 0.01$; Fig. 2C). In contrast, children in the VI+nys group made more fixations at smaller spacings during matrix search (p's < 0.01; Fig. 3C). No within-subject effects were found for the children in the VI−nys and NV group during simple matrix search (p's > 0.12). During row search children in the VI−nys group fixated longer than children in the VI+nys group at the smallest spacing ($p' < 0.1$), and tended to fixate longer than children with NV at the largest spacing ($p' < 0.1$). Spacing influenced fixation duration of children in the VI+nys group during matrix search: they fixated longer at smaller spacings (p's < 0.05; S2). Although there was a main effect of spacing on fixation duration in children in the NV group, there were no significant post hoc effects (S2). Saccade amplitudes did differ between groups during row search: saccade amplitudes were larger at 2′ for children in the VI+nys group than children in the NV group (medians resp. 2.0° and 1.2°, $p < 0.05$; Fig. 2D). Spacing influenced saccade amplitude during row and matrix search in children with NV: they made smaller saccades at smaller spacings (p's < 0.05; Fig

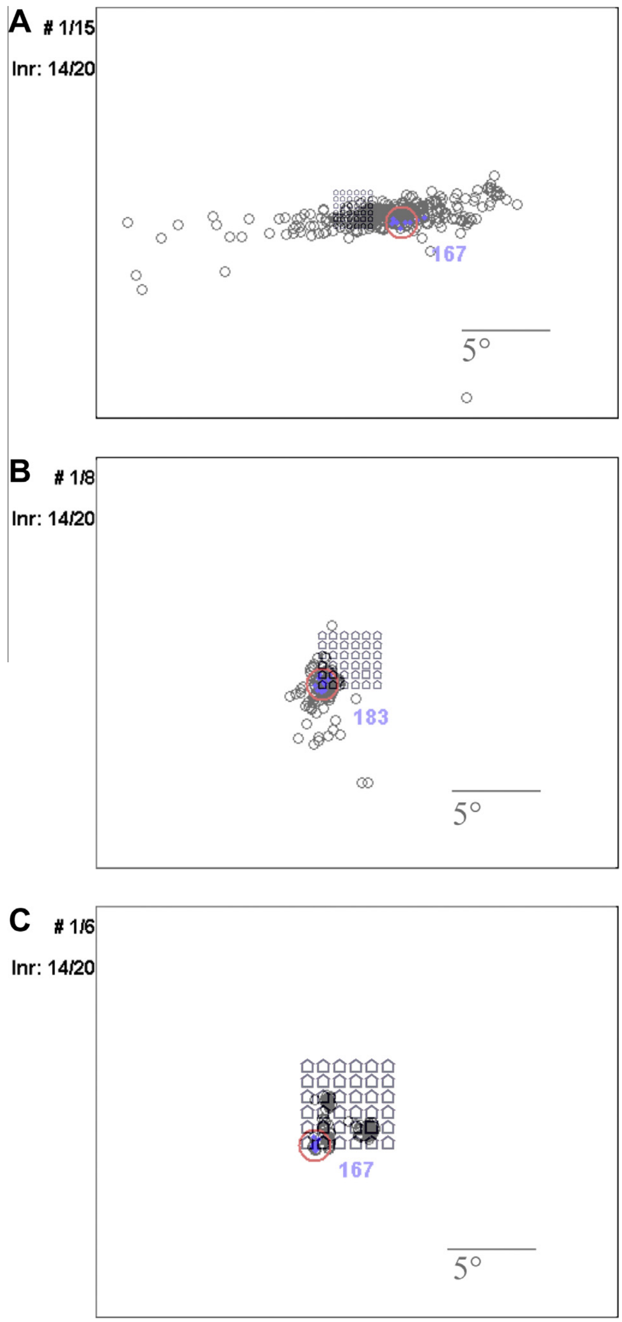


Fig. 4. Raw plots containing all fixation points for: (A) a child with visual impairment showing nystagmus, (B) a child with visual impairment without nystagmus, and (C) a child with normal vision (same trial). The two children with visual impairment gave incorrect answers. The child with normal vision gave a correct answer. As can be seen, the child with normal vision has small clusters of fixation points. The two children with visual impairment show less defined fixation clusters.

2D). Children in the VI+nys group made smaller saccades at $4'$ than $32'$ during matrix search ($p < 0.05$; Fig. 2D).

Summarizing, children with VI made more fixations than children with NV during simple matrix search and only children in the VI+nys group needed more fixations at the smaller compared to larger spacings (see Fig. 4). Children in the VI+nys group also made more fixations than children in the NV group during simple row search. Group differences in number of fixations during simple row search disappeared when spacing was $32'$. Finally, children in the VI+nys group showed larger saccade amplitudes than children with NV at $2'$ spacing during simple row search.

3.2. Effect of heterogeneous distractors

3.2.1. Performance measures: accuracy and search times

During complex matrix search groups differed in accuracy: children in the VI+nys group were less accurate than children in the NV group until at least $16'$ (p's < 0.05; Fig. 5A). Although there was a main effect of spacing on performance in the VI+nys group, there were no significant post hoc effects (S1). Search times for children with VI+nys were longer than for children with NV at all spacings except at $8'$ (p's < 0.1; Fig. 5B). Children in the VI−nys group tended to be slower than children in the NV group at $4'$ and $16'$ spacing (p's < 0.1; Fig. 5B). Search times were unaffected by spacing (p's > 0.17).

3.2.2. Eye movements

We collected 26 valid eye movement recordings (NV: 10; VI−nys: 6; VI+nys: 10). Children in the VI+nys group made more fixations than children in the NV group from $4'$ until $32'$ (p's < 0.1; Fig. 5C). None of the groups were affected by spacing (p's > 0.22). Groups also differed in fixation duration: children with VI+nys fixated shorter than children with NV (at $4'$: medians 278 ms versus 658 ms, $p < 0.05$; Fig. 5D). Only children in the NV group adjusted their fixation duration to spacing by fixating longer at smaller spacings (p's < 0.05: Fig. 5D). There were no within-subjects effects of spacing on fixation duration in the VI groups (p's > 0.29). Finally, group differences appeared for saccade amplitude. As was the case during simple row search, children in the VI+nys group made larger saccades than children in the NV group at the smallest spacing (at $2'$: medians 2.3° and 1.6°, $p < 0.05$; Fig. 5E). Saccade amplitude was not influenced by spacing in any of the groups (p's > 0.20; see S2).

3.3. Correlations between search performance and oculomotor measures

Accuracy and search times during simple matrix search were not related to the crowding ratio or any of the oculomotor measures. The only significant relation that was observed was a negative relation between the number of fixations made and the crowding ratio, $r = -0.58$. During complex visual search, accuracy was negatively related to the crowding ratio and was positively related to the saccade amplitude. Search times were negatively related to crowding ratios and showed a positive relation with number of fixations and fixation duration. Crowding ratios were only related to accuracy for serial search performance, and not for parallel search performance (see Table 3).

4. Discussion

In this study, the following three hypotheses were evaluated: (i) children in the VI+nys group show poorer performance than children in the NV group on visual search tasks with homogeneous distractors and small element spacing, (ii) there are no group differences in the row configuration, but children with VI are expected to show weaker performance than children with NV in the matrix configuration with homogeneous distractors, and (iii) children with VI show a disproportionally poor search performance on serial search tasks compared to children with NV. Error rates were high for the VI+nys group (especially during trials with small spacings), but there were no statistically significant differences in search time for correct and incorrect trials in the VI+nys group (Friedman's test), e.g. medians simple matrix search 2 minutes of arc: 8.9 s for correct trials and 6.4 s for incorrect trials, $p = 0.62$. Therefore, the VI+nys group appears to be slower compared to the NV group regardless of the correctness of trials and search times seem to be representative for this group.

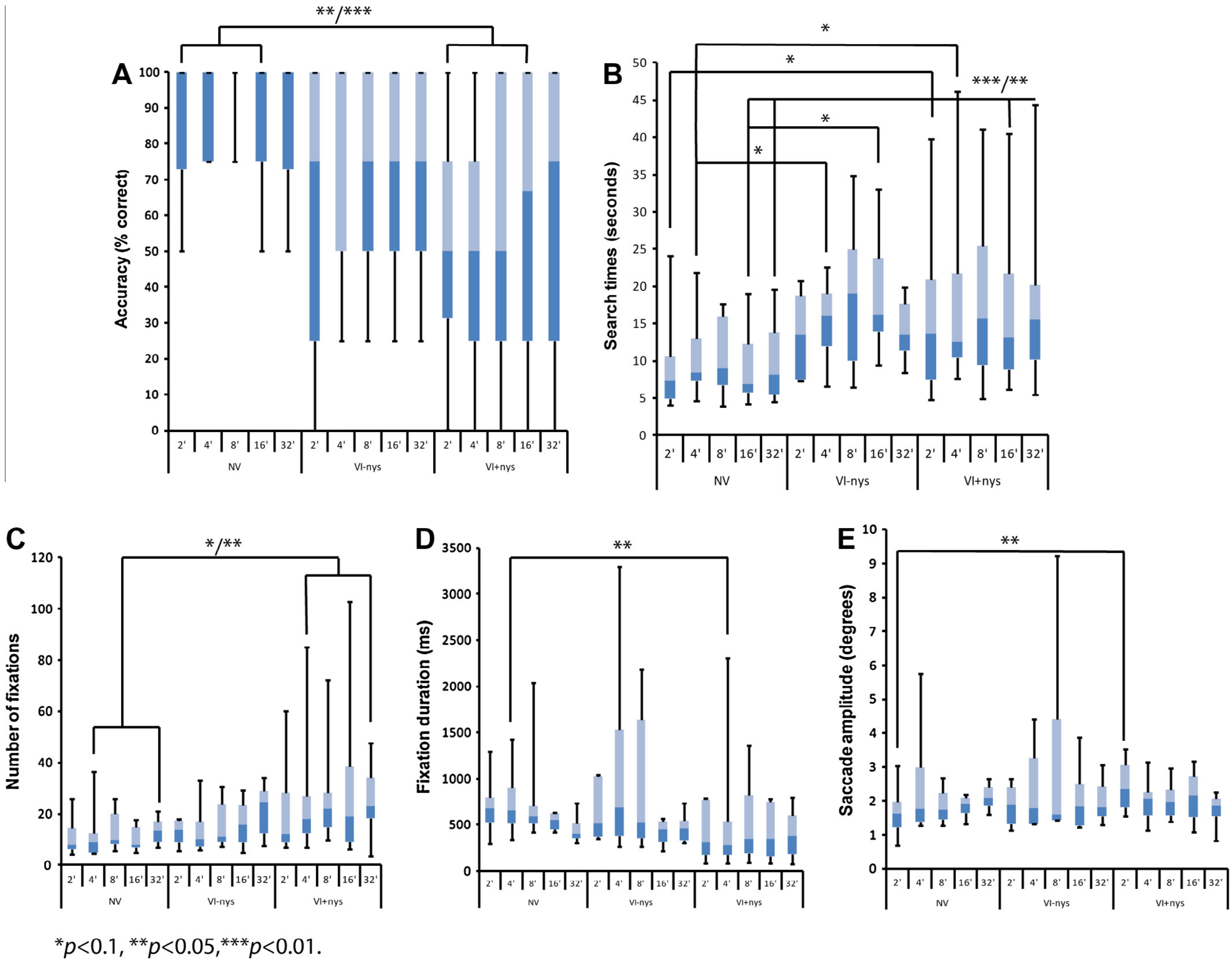


Fig. 5. Box–whisker plots for the distribution of dependent variables in the matrix configuration: (A) accuracies, (B) search times, (C) number of fixations, (D) fixation duration, and (E) saccade amplitudes. The categories on the X-axis are representative of groups: children with normal vision (NV), and with visual impairment without nystagmus (VI−), and with visual impairment showing nystagmus (VI+). *Boxes* and *whiskers*: quartiles and range, respectively.

Table 3
Correlations between performance measures, crowding ratio, and oculomotor measures for simple and complex matrix search with 2′ spacing. The matrix displays partial correlations for the VI+nys group while controlling for visual acuity.

Simple	Complex					
	Accuracy	Search time	Crowding ratio	# Fixations	Fixation duration	Saccade amplitude
Accuracy		0.17	−0.66*	−0.10	0.47	0.86**
Search time	−0.06		−0.65*	0.67*	0.70*	−0.02
Crowding ratio	0.23	0.31		−0.52	−0.38	−0.58
# Fixations	−0.07	−0.22	−0.58*		0.10	−0.05
Fixation duration	−0.23	0.17	−0.15	−0.02		0.14
Saccade amplitude	0.26	−0.26	0.28	−0.32	−0.16	

* $p < 0.05$ (one tailed p-test).
** $p < 0.01$ (one tailed p-test).

4.1. The influence of nystagmus on visual search tasks with homogeneous distractors

The first hypothesis was confirmed: children in the VI+nys group showed poorer performance on search tasks with homogeneous distractors and small element spacing than children with NV. Children in this group showed lower accuracies than children in the NV group at smaller spacings during row and matrix search. Search times were longer during simple search tasks with largest group differences occurring at small element spacings.

Our first explanation for the weaker search performance of children in the VI+nys group compared to children in the NV group is weaker oculomotor control. We found two group differences in oculomotor recordings: (i) children in the VI+nys group made more fixations than children with NV, and (ii) children in the VI+nys group showed larger saccade amplitudes than children in the NV group at 2′ spacing in two out of three conditions. The oculomotor strategy found in children in the VI+nys group, i.e. making more fixations and larger saccadic amplitudes, deviates from the strategy observed in children with NV in the present study and in previous studies in subjects with normal oculomotor control reporting smaller saccade amplitudes at smaller spacings (Vlaskamp & Hooge, 2006; Vlaskamp, Over, & Hooge, 2005). This adaptation of oculomotor strategy in children in the VI+nys group might be best explained by motor aspects that are characteristic for this group (i.e., the presence of involuntary ocular oscillations) and less from visual aspects. The oculomotor strategy we found in children in the VI+nys group has not been reported before but has been found in adults with amblyopia (more refixations during reading: Kanonidou, Proudlock, & Gottlob, 2010; larger saccade amplitudes: Shi et al., 2012).

A second explanation for the weaker performance might be found in the lack of experience with these kinds of tasks and the predictability of the task. For example, reading speed of adults with infantile nystagmus syndrome does not differ from that of adults with NV (Barot et al., 2013; Thomas et al., 2011). Eye movement data demonstrated that adults with infantile nystagmus syndrome learn to compensate for their nystagmus using a range of strategies. These strategies include taking advantage of the stereotypical and periodic nature of the involuntary eye movements to achieve the desired goal by their means (Thomas et al., 2011). However, the oculomotor strategies observed in adults with nystagmus may be resulting from experience with the expected voluntary behaviour of the eyes accumulated over many years during visual development. Such experience is obviously much less in the group of children included in our study.

4.2. Differences between row and matrix search with homogeneous distractors

The second hypothesis was partially confirmed. We expected that there would be no group differences in the row configuration, but that children with VI show weaker performance than children with NV in the matrix configuration with homogeneous distractors. The first part of our hypothesis was not confirmed: we actually did find group differences during row search. Children with VI+nys showed lower accuracies than children with NV, but there were no (within-subjects) effects of spacing on accuracy. The second part of our hypothesis was confirmed: children in the VI+nys did show lower accuracies and children in both VI groups did show longer search times than children with NV at smaller spacings. This effect was stronger in the matrix than in the row configuration.

During row search, spacing did not influence search time and accuracy of the children with VI and small spacings even facilitated search in children with NV (i.e. shorter search times at smaller element spacing). This latter finding is in line with studies indicating that patterns with discriminable elements in close proximity can be segregated more easily than patterns in which the same elements are more widely spaced (Nothdurft, 1985, 1993; Scolari et al., 2007).

An explanation for the weaker performance of the VI groups compared to the NV group during matrix search is to be sought in their lower acuity and the larger need for refixations. The partial correlations show that performance measures during simple matrix search were not significantly related to any of the oculomotor or crowding measures when controlling for acuity. The stimulus should be visible for the children with VI, because the stimulus was presented at twice the size of their threshold acuity. However, this might not be enough for the children with VI. This is in line with recent studies on reading, which report that the difference in reading acuity (smallest readable print size) and critical print size (font size below which reading is suboptimal) is 0.3 log units, i.e. factor 2, in children and adults with albinism and up to 0.6 log units, i.e. factor 4, in adults with nystagmus (Barot et al., 2013; Merrill et al., 2011). The crowding ratio was not related to accuracy for simple matrix search performance ($r = -0.23$), but the crowding ratio was related to accuracy during complex matrix search ($r = -0.66$).

A second explanation for the weaker search performance during matrix search might be masking. Masking is distinct from crowding and considered as a loss of visual information within the visual system, and crowding effects are more complex phenomena including contour interactions (a type of lateral masking), attentional factors, and fixational eye movements (Flom, 1991). Tasks that require single feature detection are immune, or nearly so, to crowding (Pelli, Palomares, & Majaj, 2004). Masking could occur during trials where the only unique target feature was located at the upper or lower site of the target (e.g., search for house surrounded by squares or vice versa). This explanation would provide an answer for: (i) the lower accuracies during small spacings in matrix search (and the lack of spacing effects during row search), and (ii) the striking drop in accuracy at the two smallest spacings. However, there was no difference in accuracy or search times between trials with unique features at the lower or upper site and trials in which targets share no features with distractors (for example, a square target between apple distractors). While our analysis does not support this masking hypothesis, future research is warranted to identify the underlying mechanisms and ideally includes a task measuring target recognition with simple flanking bars to rule out simple masking effects as an explanation.

In sum, our findings are in line with earlier research demonstrating that crowding effects are stronger for surrounding distractors placed above, below, and on both sides of the target than laterally placed distractors (Atkinson et al., 1985). Search performance was degraded by smaller element spacing during simple matrix search in all groups (manifested by longer search times), but caused greater impairment for children in the VI+nys group.

4.3. Differences between search with homogeneous and heterogeneous distractors

Our third hypothesis was confirmed: children with VI did show disproportionally poor search performance on serial search tasks compared to children with NV. This might be explained by the lack of a perceptual phenomenon called distractor–distractor grouping during search with heterogeneous distractors which is known to reduce or release crowding effects (for a review: Whitney & Levi, 2011). When distractors are grouped separately from the target, as might occur during search with homogeneous distractors, crowding effects can be reduced. In the task with heterogeneous distractors, distractors could not be grouped. Because crowding was stronger, more than twice the number of fixations were required and accuracies were lower compared to homogeneous search (in line with Ruskin & Kaye, 1990).

A second explanation for the extended group differences in the matrix with heterogeneous distractors, is the greater dependence on accurate eye movements during serial compared to parallel search (Young & Hulleman, 2013). And indeed, relations between oculomotor measures and performance measures were found even while controlling for acuity. Accuracy was negatively related to the crowding ratio ($r = -0.66$), and saccade amplitude was positively related to accuracy ($r = 0.86$). This unexpected relation between saccade size and accuracy might be due to the need to re-inspect earlier visited areas. Search time was positively related to the number of fixations ($r = 0.67$) and fixation duration ($r = 0.70$). The crowding ratio was negatively related to search time ($r = -0.65$).

We suspect that our finding is the result of an inability of the children with VI+nys to adjust saccade size and to fixate steadily, because oculomotor control appears to play a larger role when elements in a display have to be scrutinized in a serial manner. While a consistent adaptation of fixation duration and saccade amplitude was observed in the children with NV, we did not observe these adaptive abilities as strongly in our VI groups. From this perspective, oculomotor control can be seen as a prerequisite to perform a complex search tasks with small symbols.

The lower accuracies were probably not caused by attentional impairments, because group differences in accuracy disappeared at 32′ element spacing in all three search tasks. The lower accuracies of children with VI+nys were relieved by increasing element spacing, thus spacing poses a bottleneck for performance in children with VI+nys. This is in line with the outcome of the correlation analysis which shows that the crowding ratio showed a strong relation with accuracy during complex search. Thus, oculomotor control is related to performance on untrained search tasks, especially when there is a need for accurate fixational eye movements and densely spaced elements have to be disentangled.

5. Conclusions

The present work indicates that children with VI (with and without nystagmus) show longer search times on visual search tasks with homogeneous distractors compared to children with NV. The difference between groups is larger for matrix search than for row search. Furthermore, children with VI+nys showed lower accuracies on search tasks with homogeneous distractors than children with NV at the smallest spacings, and group differences increased for matrix search with heterogeneous distractors. Group differences in accuracy disappeared at the largest element spacing. Visual search performance is weaker when distractors surround the target in all directions than when distractors only surround the target laterally. A practical implication that can be extracted from this study is that increasing vertical interline spacing, or introducing a typoscope which isolates 1 or 2 lines on a page (Rowe & VIS group UK, 2007), could be beneficial for children with VI.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2014.01.004.

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